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A method for determination of the dimensions of seismic shear walls in buildings

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ABSTRACT

A lateral load carrying system consisting of only shear walls is used generally for structures having 14 storeys or more. It can be seen that the effect of earthquakes in the systems consisting of the shear walls or shear walls-core are very small. For resisting earthquake effects it is proposed to construct shear walls which are perpendicular to each other in plan and having the cross sectional area 1.5% of the building. Unfortunately in this proposal, the effect of number of storeys and the division of shear wall area to the necessary parts is not taken into consideration. In this paper, these factors are considered as, number of storeys, plan area of a storey, earthquake risk zone, material properties and shear wall thickness. The criteria for determination of the dimensions of earthquake shear walls which are suitable for architectural considerations of the building are given. For various storey areas and 10 storeys, the lengths of shear walls which ensure the suggested criteria, having the same length are given in diagrams. It is also shown how to find the length of shear walls under the same conditions if there are more than 10 storeys.

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1. Introduction

In our country, it is preferred to build structures both under horizontal and vertical loadings by the use of frame systems, till 6 storeys in the first earthquake risk zone and 7 storeys in the second earthquake risk zone. In frame systems, because of the reasons of more storeys, greater cross-section areas for beams and columns especially at the lower storeys or large relative displacements between the storeys lead to build the frame structure with shear walls. The obligation of using lifts in buildings having 6 storeys or more leads a lift-house in the means of core. A lateral load carrying system consisting of only shear walls is used generally for structures having 14 storeys or more (ATC22, 1989; Tarenath, 1988; Wakabayashi, 1988; Paulay and Priestley, 1992; Özden and Kumbasar, 1993; Celep and Kumbasar, 2004). However, in these systems, for limiting the thickness of the slabs, some of the vertical loads can be transferred to foundations by the use of columns which do not carry horizontal loads if needed. From the observations made in the earthquake regions after an earthquake event, large damages can be seen in frame system structures having 4-8 storeys, frame-shear wall (+core) system structures having 7-13 storeys (Fintel, 1991).

The main reasons of the earthquake damages are not applying the codes in the design and construction of the structures such as; a) not obeying the constructive rules for reinforcement lay-out in beam-column or beam-shear wall joints (such as development length, stirrups, etc.), and less shear capacity than bending capacity in these zones, b) the occurrence of plastic hinges on columns before beams, c) neglecting of the torsional effects in calculations, d) unassured ductile system, e) structural irregularities, f) less concrete strength usage than design strength, g) not taking into account of foundation soil properties while calculating the earthquake forces, h) unsuitable foundation system.

It can be seen that the effects of earthquakes in the systems consisting of the shear walls or shear walls-core are very small. This is confirmed in a detailed manner by Fintel (1991) and although the behaviour of systems

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consisting of shear walls having diagonal cracks after an earthquake have some points which are necessary to investigate, these systems are the best solutions for earthquake resistance (Altın, 1989; Fintel, 1991). This property of shear walls is also seen by Ersoy (1993) and proposed to construct shear walls which are perpendicular to each other in plan and having the cross sectional area 1.5% with respect to building area for earthquake effects (Ersoy, 1993). Unfortunately, in this proposal, the effect of number of storeys and the division of shear wall area to the necessary parts is not taken into consideration.

In this paper, these factors are considered as; a) number of storeys, b) plan area of a storey, c) earthquake risk zone, d) material properties, e) selected shear wall thickness, f) the criteria for determination of the dimensions of earthquake shear walls. Constructed buildings having different storey areas and storey weights are considered and by the use of TS498 (2000) and TNC (2000), the average weight for percent area is determined for single storey. Then, the total shear force, the overturning moment, the minimum and maximum values of axial forces of the shear walls at the basement and the top force V_t are calculated for the buildings having number of storeys from 2 to 10 and A_p storey areas from 100 m^2 to 800 m^2. The criteria for determination of the dimensions of earthquake shear walls which are suitable for architectural configurations of the building are given. For storey areas A_p, from 800 m^2 to 100 m^2 and number of storeys n=10, the lengths of shear walls are given which ensure the criteria, having the number of shear walls n_b=3-10 with the same length in part 4. It is also shown how to find the length of shear walls under the same conditions if there are more than 10 storeys. Numerical examples are given and the results are listed in conclusion part.

2. Average Vertical and Horizontal Loads

Observations made on the constructed buildings having various storey heights, storey areas and usage (such as houses, offices) show that the average uniform vertical load of a storey can be accepted as m=12 kN/m^2. In the present paper, the behaviour of the slabs of structures made of shear walls is taken as flat-slabs with the thickness of 200 mm. The total weight of the building over the foundation can be evaluated as

$$W = NmA_p \,, \tag{1}$$

where N is the number of storeys and A_p is the storey area. The total vertical force summation of the shear walls W_p above the foundations is about 50, 75 and 100% of the total building weight W. Different values of percentage is taken into account for shear wall system and for shear wall-frame system, separately, like;

$$W_p = 0.75W = 0.90NA_p \ , \ W_p = 1.00W = 1.20NA_p \,, \tag{2}$$

$$W_p = 0.50W = 0.60NA_p \ , \ W_p = 0.75W = 0.90NA_p \,. \tag{3}$$

The calculation of the horizontal loads is made according to TNC, 2007. Total shear force just above the foundation V_t can be written together with Eq. (2).

$$V_t = WA(T_1)/R_a(T_1) \geq 0.10A_0IW \,,$$
$$A(T_1) = A_0IS(T) \ , \ T_1 \cong T_{1A} = C_tH_N^{3/4} \,. \tag{4}$$

In this calculations, A_0 effective ground acceleration coefficient, importance factor I=1.00, C_t=0.03~0.04 (shear wall system), C_t =0.05 (shear wall-frame system), T_{1A}= 0.09 $H_N/\sqrt{L}$ (for H_N>25 m, L is the building length in seismic direction) are taken into account. Seismic load reduction factor $R_a(T_1)$ and structural behaviour factor R are taken as 6.00 for shear wall system and as 7 for shear wall-frame system.

Accepting a triangularly variation for V_t along the height of the building H_N; w_n can be written as w_n=2V_t/H=2$V_t/(Nh)$ at the top. Here, h is the storey height. In this study, storey height is assumed as 3.00 m.

The overturning moment M_T and the shear force V_t at the base of the building are

$$M_T = (2/3)H_NV_t \,. \tag{5}$$

3. The Criteria for Shear Wall Determination

The suggested criteria for determination of the dimensions of earthquake shear walls are listed in the following (TS500, 2000; TNC, 2007):

1) The compression depth of the shear walls at the base with high ductility should be

$$k_x = \frac{x}{d} = \varepsilon_{cu}/(\varepsilon_{cu} + \varepsilon_s) \leq 0.423 \,. \tag{6}$$

Under this condition ε_s is

$$\varepsilon_s \geq 0.0041 \,, \tag{7}$$

which is 2.05 multiple of ε_{ys} for f_{yk} =420 N/mm^2 (NBC, 1985; TS500, 2000; Celep and Kumbasar, 2005). The structure behaviour coefficient should be estimated according to the situation if the ductility is not increased.

2) The ratio of the total area of vertical reinforcement at each wall end zone to the gross wall cross section area should not be less than 0.001. However this ratio shall be increased to 0.002 along the critical wall height. The reason for this criteria is to assure a suitable concreting and is existing of the fifth criteria.

$$\rho \leq 0.002 \text{ (along the critical wall height)}. \tag{8}$$

3) The relative storey displacement Δ_i is

$$\Delta_i = d_i - d_{i-1} \leq 0.003h_i \,, \tag{9}$$

where d_i is the displacement of i-th floor and h_i is the storey height. According to this, the ratio of shear wall top horizontal displacement f to the building height H is θ which is

$$\delta_i = R\Delta_i \ , \ \delta_{i(max)}/h_i \leq 0.02\,. \tag{10}$$

This criteria supplies the second order effects to be negligible.

4) It is necessary to ensure a sufficient shear force capacity of the shear walls so that there should not be any diagonal cracks in shear walls at the ultimate state. This criteria assures, if the smaller principal concrete stress is negative on the center of gravity of the shear wall above the basement, then the absolute value of this should be smaller than a proper value (TS9967, 1992). With the axial stress σ_c caused by vertical loads and the shear stress τ_c caused by shear forces in the center of gravity of the shear wall, the small principal stress σ_1 is known to be

$$\sigma_1 = \left(\frac{\sigma_c}{2}\right) - \sqrt{(\sigma_c/2)^2 + \tau_c^2}\,. \tag{11}$$

If σ_1 is negative, then the criter can be expressed as $|\sigma_1|<\sigma_1^*$, where $\sigma_1^*=0.043f_{ck}$ and f_{ck} is the characteristic compressive strength of the concrete.

An i-th shear wall's shear force V_{Ti} above the foundation and the axial force N_{Ti} caused by vertical loads with the shear wall width b_i and length l_{Ti} then with the stresses $\sigma_{ci}=N_{Ti}/b_il_{Ti}$ and $\tau_{ci}=V_{Ti}/b_il_{Ti}$. Eq. (11), for σ_1 being negative, the absolute value can be written as,

$$|\sigma_1| = \left|\left(\frac{1}{2b_il_{Ti}}\right)\left(N_{Ti} - \sqrt{N_{Ti}^2 + 4V_{Ti}^2}\right)\right| \leq \sigma_1^*\,. \tag{12}$$

By using these equations, the shear wall lengths which satisfy the criteria can be obtained. For $C=A(T_1)/R_a(T_1)$,

$$l_{Ti} = \frac{\left[2.85NA_p\left(1-\sqrt{1+16C^2}\right)\right]}{b\sigma_1^*} \quad \text{for} \quad N_T = 0.50W\,,$$

$$l_{Ti} = \frac{\left[4.28NA_p\left(1-\sqrt{1+7.11C^2}\right)\right]}{b\sigma_1^*} \quad \text{for} \quad N_T = 0.75W\,,$$

$$l_{Ti} = \frac{\left[5.7NA_p\left(1-\sqrt{1+4C^2}\right)\right]}{b\sigma_1^*} \quad \text{for} \quad N_T = 1.00W\,. \tag{13}$$

From Eqs. (13), it is obvious that l_{Ti} inversely proportional to f_{ck} and b and right proportional to N. Eq. (14) can be obtained with the condition A_p and C to be the same for two different values of n, b and f_{ck} which leads a relation with different shear wall lengths l_{Ti}.

$$l_{T2} = l_{T1}\left(\frac{N_2}{N_1}\right)\left[\frac{f_{ck}^{(2)}}{f_{ck}^{(1)}}\right]\left(\frac{b_1}{b_2}\right). \tag{14}$$

Shear wall lengths l_{Ti} are given in diagrams which are calculated from Eq. (13) for n=10 storeys, f_{ck}=20 N/mm², b=200 mm and for various values of A_p, A_0 and N_T. For shear wall lengths in the plan l_{bi} which are suitable to the building plan, being larger than l_{Ti},

$$l_{Ti} < l_{bi}\,, \tag{15}$$

the diagonal crack criteria is clearly ensured. If the shear wall has a cross-section like [, L , I ; then this criteria should be controlled. This criteria also takes place in the Romanian Code for Precast Structures 1972 and TS 9967. Horizontal load capacity of shear walls having diagonal-cracks contains some unclear points to be investigated.

5) The shear force capacity should be greater than the bending moment capacity in shear walls. This prevents the diagonal-cracks and can be obtained by the longitudinal reinforcement ratio less than 0.002 at the end cross-sections of the shear walls ($l_{bi}b$). It means that if the second and fourth criteria are ensured then the fifth criteria is also ensured. The shear force V_e shall be taken into account in calculating the transverse reinforcement in walls. Shear strength of wall cross sections V_r shall be calculated with Eq. (16). The shear force V_e shall satisfy the conditions defined below.

$$V_e \leq V_r \ , \ V_e \leq 0.22A_{ch}f_{cd}\,,$$

$$V_r = A_{ch}(0.65f_{ctd} + \rho_{sh}f_{ywd}) \ , \ V_r \leq A_{wf}f_{yd}\mu\,. \tag{16}$$

6) Structural walls are the vertical elements of the structural system where the ratio of length to thickness in plan is equal to at least seven (l_w/b_w>7). In buildings where seismic loads are fully carried by structural walls along the full height of building, wall thickness shall not be less than 1/15 the highest storey height and 200mm, provided that both of the conditions given by Eq. (17) are satisfied.

$$\sum A_g/\sum A_p \geq 0.002 \ , \ V_t/\sum A_g \leq 0.5\, f_{ctd}\,. \tag{17}$$

4. Evaluation of Shear Wall Lengths

The number of the shear walls having equal length on each side of the building can be n_b=3-10. Let us express the length of each shear wall by l_{bi} under the condition that A_0, A_p, n, n_b, f_{ck} and b are constant. The moment of inertia for a single shear wall I_{bi} and overturning moment M_{bi} and shear force V_{bi} at the foundation are

$$l_{bi} = bl_{bi}^3/12\,,$$

$$M_{bi} = M_Tl_{bi}/\sum I_{bi} \ , \ V_{bi} = V_Tl_{bi}/\sum I_{bi}\,. \tag{18}$$

The total moment of inertia for all shear walls can be expressed as a single shear wall with the moment of inertia. The elastic horizontal displacement f of the structure top edge can be calculated and its ratio to the structure height θ can be written. After the calculation of overturning moments, shear forces and axial forces of the shear walls, reinforcement can be calculated by ensuring the first and the second criteria. The non-dimensional axial force n_i and the non- dimensional overturning moment m_i and the l_{bi} lengths can be calculated. For the determination of l_{bi}, it should be used the calculated l_{bi} lengths corresponding to the values of n_i or m_i due to the first and the second criteria. The lengths of shear walls, for n=10 storeys and equal shear wall lengths with the numbers n_b=3-10 are evaluated. Without giving the details of the calculations, for A_p from 100 m² to 800 m², b=0.20 m, A_0=0.10 and 0.40, f_{ck}=20 N/mm² and N_T=(0.50-1.00)W, the l_{bi} lengths are calculated and the values of θ, ρ, ε_c, ε_s and k_x are given in the diagrams. It should be noted that the calculated l_{bi} lengths for a specific number of storeys such as n=10, should be multiplied by

$$\eta = n^*/10\,. \tag{19}$$

As seen in Eqs., and under the same conditions but different number of storeys as $n=n^*\neq 10$, the lengths of shear walls will be obtained. On the other hand, the k_x, ρ and θ values obtained for $n=n^*$ and for n=10 under the same conditions are equal to each other.

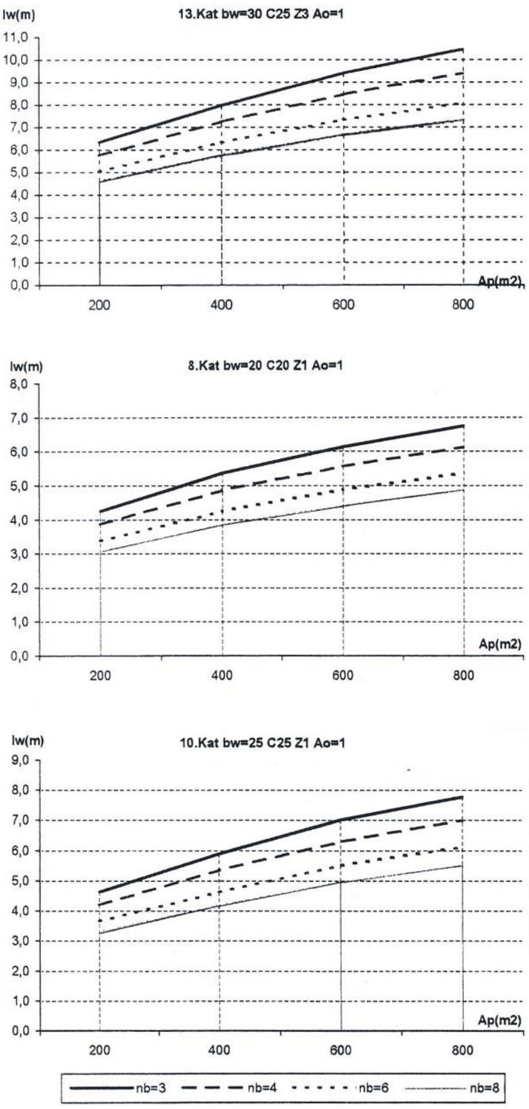

Fig. 1. Shear wall length diagrams.

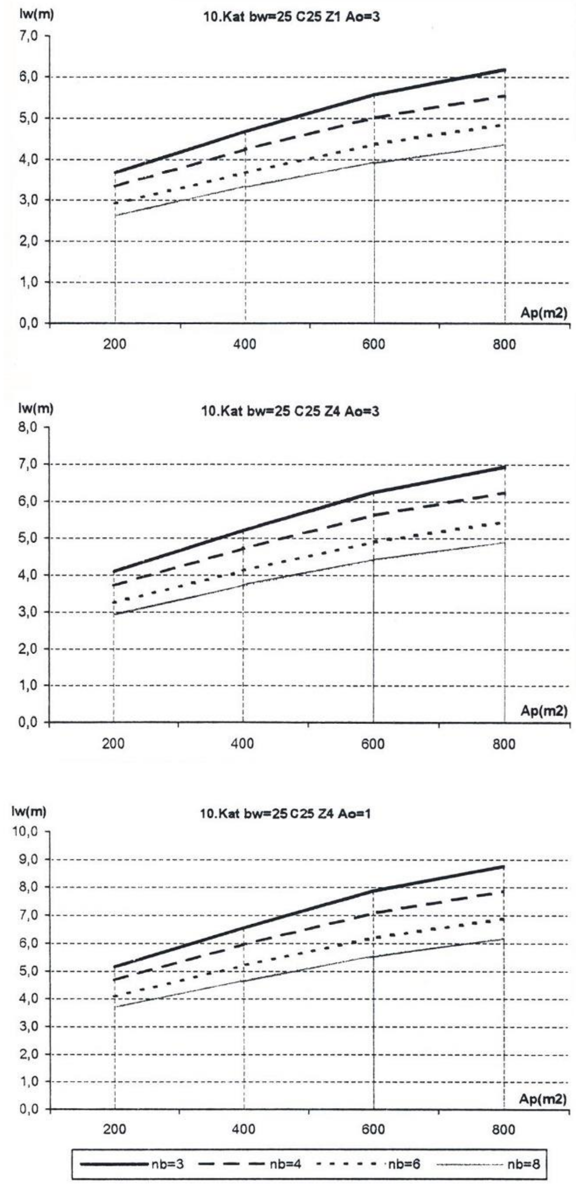

Fig. 2. Shear wall length diagrams.

Examination of the diagrams yields the following:

a) Generally it can be said that, for larger values of A_p while N_T=0.50W, k_x reaches 0.423 and ρ is very low with comparison to 0.001 but for decreasing A_p, instead of upper limit for k_x, the second criteria which makes ρ=0.001 should be taken into consideration. In the situation of decreasing axial force, instead of k_x, it can be seen that ρ can reach more easily to the upper limit.

b) When the axial force is large while there is small storey area, the l_{bi} length of one of the shear walls having the same length can be greater than the length $n_b l_{Ti}$.

c) Shear walls calculated according to the first and the second criteria, always ensure the fourth criteria.

d) Value for θ is also given. As it is seen, when the l_{bi} lengths are calculated according to the first and the second criteria, the third criteria is also ensured.

On the other hand, as the lengths of the shear walls are defined in the architectural plan, the shear walls in the same direction can have different lengths.

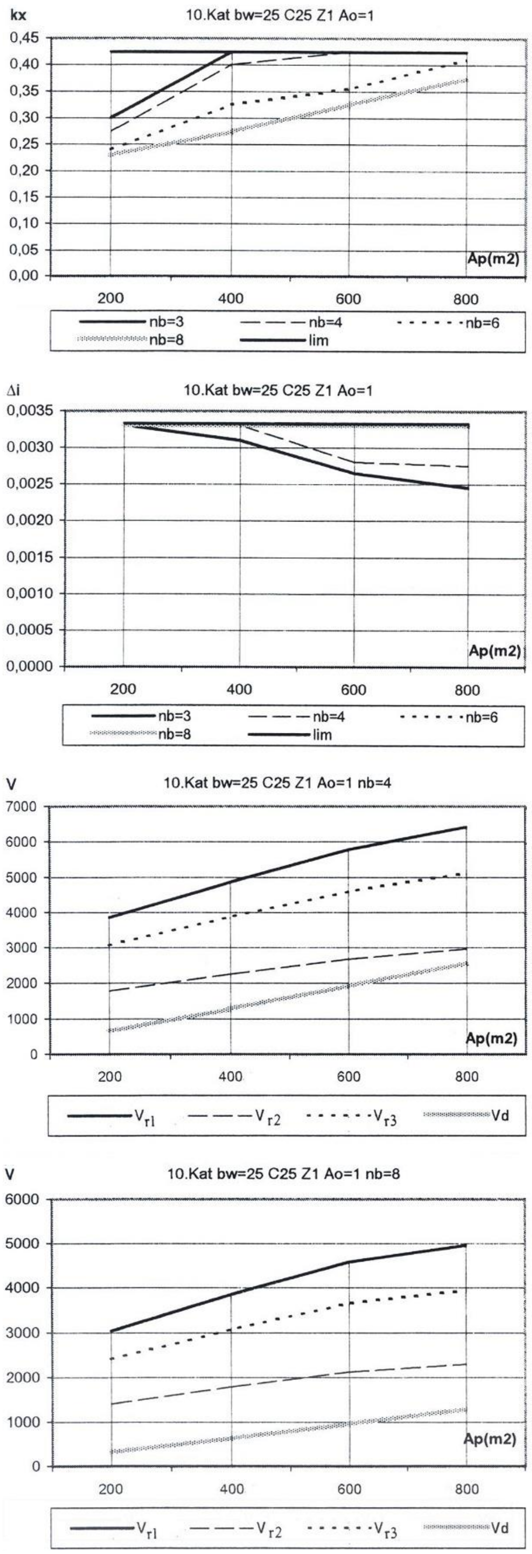

Fig. 3. k_x, storey displacement and shear force diagrams.

After dimensioning the shear walls by the minimum thickness given in earthquake codes, solutions of them under earthquake effects are made for structure behaviour coefficient for increased ductility and the overturning moment, shear force and axial force at the foundation is calculated. Then the necessary reinforcement can be calculated according to TS500, 2000 and the unit deformations ε_c and ε_s are established, which means that k_x and ρ are also established.

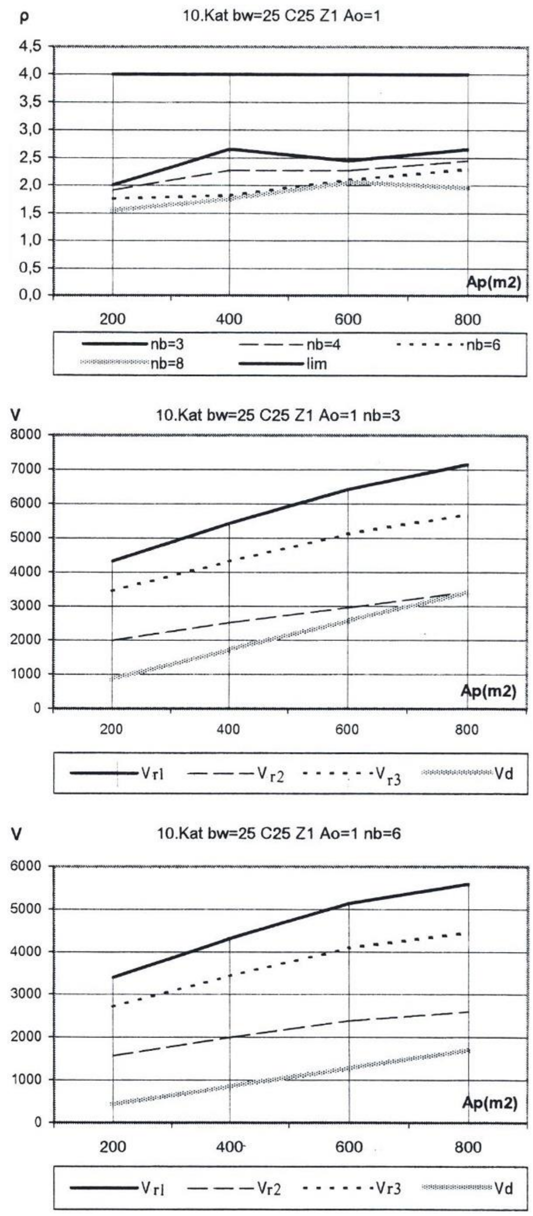

Fig. 4. ρ and shear force diagrams.

The first and the second criteria can be controlled with these, respectively. In case of exceedance of the limits for one of the criteria, one of the following steps can be made to ensure; a) changing the thickness of the shear wall, b) changing the length of the shear wall, c) adding another shear wall to the system. When the second criteria is ensured while the first criteria is not, which means the acceptance of non-increased shear wall ductility by the project- engineer, than the structure behaviour coefficient should be taken suitable to this situation and the earthquake forces should be recalculated.

5. Numerical Examples

5.1. Shear wall systems

The structural system consist of shear walls which will carry the horizontal loads in the earthquake risk zone. Storey area of the building is 600 m^2.

a) For seismic zone 1 (A_0=0.40), soil group Z3, N=13, material C25-S420a, n_b=6, b_w=30 cm, from Fig. 1, shear wall length is taken as l_w=740 cm.
With these values, W=96300 kN, T_1=0.784 s,
$S(T)$=2.018, V_t=12590 kN, M_t =336323 kNm.
P1 shear wall; n=0.130, m=0.204, k_x=0.300<0.423,
ω=0.15, ρ=%3.4. P2; k_x=0.333, ρ=%3.3. P3; k_x=0.353,
ρ=%3.1. P4; k_x=0.400, ρ=%2.9,
Shear forces;
V_d=2098 kN , V_e<V_r , V_r=0.22$A_{ch}f_{cd}$=8140 kN,
ρ_{sh}=0.0025 , V_r=A_{ch}(0.65f_{ctd}+ $\rho_{sh}f_{ywd}$)=3758 kN,
V_r=$A_{wf}f_{yd}\mu$=6260 kN , $(\delta_i)_{\max}/h_i$=0.00333≤0.02
(H_w/l_w)=0.878<2 , (b_w/h)=1/10≥1/15.
b) For seismic zone 1 (A_0=0.40), soil group Z1, N=13, material C25-S420a, n_b=6, b_w=30 cm, l_w=620 cm.
c) For seismic zone 1 (A_0=0.40), soil group Z3, N=18, material C30-S420a, n_b=6, b_w=30 cm, l_w=940 cm.
d) For seismic zone 1 (A_0=0.40), soil group Z3, N=18, material C30-S420a, n_b=6, b_w=35 cm, l_w=890 cm.

5.2. Shear wall and frame systems

The structural system consist of shear walls and frames which will carry the horizontal loads in the earthquake risk zone. Storey area of the building is 400 m^2. W_p=0.75W.
a) For seismic zone 1 (A_0=0.40), soil group Z1, N=8, material C20-S420a, n_b=4, b_w=20 cm, l_w=480 cm.
b) For seismic zone 3 (A_0=0.20), soil group Z1, N=8, material C20-S420a, n_b=4, b_w=20 cm, l_w=390 cm.
c) For seismic zone 1 (A_0=0.40), soil group Z3, N=15, material C30-S420a, n_b=4, b_w=25 cm, l_w=870 cm.
d) For seismic zone 3 (A_0=0.20), soil group Z3, N=15, material C30-S420a, n_b=4, b_w=25 cm, l_w=690 cm.

The selected shear walls ensured the criteria given in part 3.

6. Conclusions

In this study, the calculation of systems consisting of shear walls which are perfectly resistant under earthquake effects and can be built quickly, is examined.

To determine the dimensions of earthquake shear walls in buildings, the following criteria are proposed. a) It is desired to have increased ductility in the structures which will be constructed in the first and the second degree earthquake risk zones. According to this, the k_x of the shear walls at the base with high ductility should be less than 0.423, b) The total reinforcement at the end cross-sections of the shear walls should be less than 0.002, c) The ratio of shear wall top horizontal displacement to the building height should be less than 0.02, d) There should not be any diagonal cracks in shear walls, d) The shear force capacity should be greater than the bending moment capacity in shear walls.

The average storey weight for percent area is determined by the use of TS498, 2000 and TNC, 2007 for constructed buildings having different storey areas in case of storey weights calculated for earthquake calculations. Total shear force, the overturning moment, the minimum and maximum values of axial forces of the shear walls at the basement and the top force are calculated for the buildings having number of storeys from 2 to 10 and storey areas from 100 m^2 to 800 m^2.

For N=10 and shear walls with the same size, the calculated l_{Ti}, l_{bi}, θ, ρ, ε_c, ε_s and k_x values for various n_b, A_0, A_p and W_p suitable to the first and the second criteria are given in diagrams.

With the same conditions but different number of storeys from N=10, such as N=N^*, the necessary lengths of shear walls l_{bn}^* can be calculated as l_{bn}^*=$(N^*/10)l_{b10}$. On the other hand, the θ, ρ and k_x values obtained for l_{bn}^* and for l_{b10} under the same conditions are equal to each other.

Lengths of shear walls can be pre-dimensioned before calculations by the use of these tables. Certainly, a definite calculation is necessary. It is explained how to design, if the lengths of the shear walls are given according to the architectural design, in part 4. The shear force which will be carried by the shear walls, should be less than defined maximum value.

Shear walls having cross-sections of [, L , I will be considered in another study.

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